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Experimental and Numerical Investigation on Charcoal - Stabilized Black Cotton Soil

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Abstract: This paper presents the use of charcoal powder as a sustainable stabilizer for black cotton soil. The natural soil is classified as CH soil.CBR of 3.0, and UCS of 3.17 kg/cm². Charcoal added at 5–40% improved soil behaviour, Strength parameters increased significantly, achieving a maximum CBR of 10 at 20% charcoal and a peak UCS of 8.5 kg/cm² at 10% charcoal. Slope stability analysis for earthen dams using PLAXIS 2D showed FoS values of 1.54 for natural soil, 1.57 for 20%, and 1.569 for 30% charcoal mixes. Overall, 10–20% charcoal provided optimum improvement in strength, workability, and stability, confirming its suitability as an eco-friendly stabilizer for embankments and pavement subgrades.
Keywords: Charcoal Powder, Expansive Soil, Stabilization, CBR, Slope stability.

I. INTRODUCTION

Soil stabilization is essential in geotechnical engineering to enhance the strength, durability, and stability of weak soils for infrastructure applications. Traditional stabilizers like cement and lime improve soil performance but contribute to high costs and carbon emissions.

Hence, sustainable alternatives such as charcoal powder are gaining attention for being eco-friendly and cost-effective.Black cotton soil, known for its high swelling and shrinkage due to montmorillonite minerals, poses serious challenges in construction. Stabilization with charcoal powder helps reduce its plasticity, swelling potential, and moisture sensitivity while improving strength parameters like CBR and UCS. Charcoal's lightweight, porous, and carbon-rich nature enhances soil structure, reduces water absorption, and improves drainage, making it suitable for embankments and subgrades.In this study, varying percentages of charcoal (10%, 20%,30% and 40%) were added to black cotton soil to analyze their effects on strength and slope stability. Laboratory tests and PLAXIS 2D simulations showed that the inclusion of charcoal increased cohesion, internal friction angle, and Factor of Safety (FOS), indicating improved slope stability and load-bearing capacity.Overall, charcoal stabilization proves to be an efficient, sustainable, and environmentally responsible solution for improving black cotton soil, supporting long-term stability and eco-friendly infrastructure development.

II. OBJECTIVES

1) To determine the effect of charcoal powder on the geotechnical properties of expansive clay soil.
2) To identify the optimum mix proportions for maximum improvement in strength and stability.
3) To evaluate Factor of safety by using slope stability analysis in plaxis 2D.

III. MATERIALS AND METHODS

A. Black Cotton Soil

The clay soil utilized in this study was sourced from a lake near Patanchervu in the Medchal-Malkajgiri District of Telangana, where it had been kept in an open area which is shown in figure 3.1. The collected soil samples were tested according to the specifications outlined in the relevant Indian Standards test codes and stored in a laboratory under controlled conditions for the experiments. Fundamental tests are conducted to characterize the soil, assessing parameters such as Grain size distribution, Atterberg limits, Modified compaction, California Bearing Ratio, Unconfined Compressive Strength. The results of these soil properties are presented in Table 2.

B. Charcoal

The charcoal used in this study was obtained from industrial waste at Langarhouse, Medchal-Malkajgiri District,Telangana. Charcoal, also known as biochar, is a carbon-rich porous material produced through the pyrolysis of organic matter. When mixed with black cotton soil, it improves strength, reduces plasticity, and minimizes swelling and shrinkage. Its porous structure enhances drainage and compaction characteristics, while the carbon content strengthens particle bonding. Typically, 10–40% charcoal by weight is used to improve parameters like CBR and UCS. Owing to its low cost, sustainability, and environmental benefits, charcoal serves as an effective and eco-friendly soil stabilizer.

C. Mix Proportion

The mix proportions adopted for this study are presented in Table 1, showing five sets of soil samples treated with varying percentages of charcoal.

Table 1: Mix proportion

Sample	Charcoal (%)
1	0
2	5
3	10
4	20
5	30
6	40

The table represents six soil samples (1–6) prepared with different charcoal contents ranging from 0% to 40%. The untreated soil (Sample 1) serves as the control, while Samples 2 to 6 include increasing percentages of charcoal. These varying proportions were selected to study the effect of charcoal content on the strength, compaction, and plasticity characteristics of black cotton soil and to determine the optimum dosage for stabilization.

D. Preliminary Tests

The following laboratory tests were conducted on black cotton soil to determine its fundamental engineering properties and evaluate the effects of charcoal addition:

Atterberg' limits, Grain size distribution, Modified compaction test, California Bearing Ratio, Unconfined Compressive Strength

E. Experimental Study on Black Cotton Soil Mixed with Charcoal

Charcoal was added to black cotton soil in varying proportions of 10%, 20%, 30%, and 40% by dry weight. The mixes were tested to evaluate improvements in engineering properties. Tests conducted included Atterberg's limits, Modified Proctor (MDD & OMC), UCS, CBR, and Grain size distribution. These experiments aimed to determine the optimum charcoal content that enhances strength, compaction, and stability of black cotton soil.

IV. RESULTS AND DISCUSSIONS

Basic properties of untreated Black Cotton Soil given in table 2

Table 2: Basic Properties of Soil

Properties of Soil	Values
Liquid limit (%)	53
Plastic limit (%)	32
Plasticity index (%)	21
Clay and Silt fraction (%)	83.5
soil classification	CH
Optimum Moisture Content (%)	20
Maximum Dry Density(kN/m3)	15.8
Shear Strength(kN/m^2)	317
Cohesion (kN/m^2)	158
California Bearing Ratio	3

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A. Properties of Soil Treated with Charcoal

Atterberg's limit test, Unconfined Compressive Strength (UCS) test, Heavy Compaction test, and California Bearing Ratio (CBR) test were conducted to evaluate the changes in the engineering properties of black cotton soil treated with varying percentages of charcoal (10%, 20%, 30%, and 40%). These tests were performed to assess the effect of charcoal addition on the soil's plasticity, compaction characteristics, strength, and load-bearing capacity, thereby determining the optimum percentage of charcoal for effective stabilization.

Table 3: Variation of Atterberg's Limits with Charcoal content

Charcoal (%)	Liquid Limit (LL) (%)	Plastic Limit (PL) (%)	Plasticity Index (PI) (%)	Remarks
0	52	32	20	Untreated soil (control)
10	55	23	32	Slight increase in LL and PI due to enhanced porosity
20	64	26	38	Maximum LL and PI observed; optimum charcoal content
30	61	26.3	34.7	LL and PI start decreasing; improved stability
40	56	34	22	Lowest PI; reduced swelling and shrinkage potential

The liquid limit increases up to 20% charcoal and then decreases with further addition. The plastic limit rises steadily with higher charcoal content, while the plasticity index peaks at 20% and then drops sharply at 40%. This indicates that moderate charcoal content improves plasticity, whereas higher content enhances soil stability and reduces swelling tendency.

Table 4: Variation of Maximum Dry Density (MDD) with Charcoal Content

Charcoal (%)	Maximum Dry Density (MDD) (g/cc)	Observation
0	1.58	Untreated soil
5	1.52	Slight reduction; improved particle arrangement and packing
10	1.48	Good compaction; optimum particle interlocking observed
20	1.45	Gradual reduction due to lightweight charcoal particles
30	1.24	Noticeable decline; increased voids lower density
40	1.19	Minimum MDD; excessive charcoal reduces compaction efficiency

The MDD decreases progressively as charcoal content increases from 0% to 40%. The highest compaction efficiency is achieved between 5% and 10% charcoal, where soil particles are well-packed. Beyond 20%, the low density and high porosity of charcoal significantly reduce the overall dry density of the soil.

Table 5 : Variation of CBR and UCS values with Charcoal Content

Charcoal (%)	CBR Value (%)	UCS (kg/cm^2)
0	3	3.3
5	3.5	4.2
10	7.2	8.5
20	10.4	4.8
30	9	4.1
40	8.5	3.6

The results indicate that both CBR and UCS values increase significantly with the addition of charcoal up to an optimum level, beyond which the strength parameters begin to decline. The optimum charcoal content is observed between 10% and 20%, where the CBR value reaches 10.4% and UCS attains 8.5 kg/cm², showing major improvement compared to untreated soil. This enhancement is attributed to better particle bonding, reduced plasticity, and improved compaction. However, at higher charcoal percentages (30–40%), both CBR and UCS decrease due to the lightweight and porous nature of charcoal, which lowers soil density and cohesion. Hence, moderate charcoal addition (around 10–20%) provides the best stabilization effect, improving both strength and load-bearing capacity of black cotton soil.

Table 6: Properties of Soil after treated with Charcoal

Charcoal Content (%)	(LL) (%)	(PL) (%)	(PI) (%)	(OMC) (%)	(MDD) (g/cc)	CBR (%)	(UCS) (kg/cm²)	(c) (kg/cm²)	Remarks / Interpretation
0 (Natural Clay)	53	31.9	21.1	20	1.58	3.06	3.17	1.58	Baseline soil; low strength and high plasticity; poor compaction and loadbearing capacity.
5% Charcoal–Clay Mix	54.2	28	26.2	20	1.5	3.5	5.6	2.8	Slight improvement in strength and density; minor reduction in plasticity; early indication of stabilization.
10% Charcoal–Clay Mix	55.5	22.9	32.6	20	1.47	7.15	8.51	4.25	Optimum bonding and strength; notable rise in UCS and CBR; reduced density aids slope stability.
20% Charcoal–Clay Mix	64.08	26	38.8	20	1.44	10.4	4.89	2.44	Highest CBR achieved; strong subgrade potential; moderate UCS; good compaction and loadbearing.
30% Charcoal–Clay Mix	61.5	26.3	35.2	20	1.24	8.9	3.97	1.98	Moderate stability; lower density; excessive charcoal weakens bonding and reduces stiffness.
40% Charcoal–Clay Mix	56.2	34.61	21.59	20	1.19	4.5	3.71	1.85	Overstabilized; high porosity and low cohesion; poor compaction and reduced strength.

Using the laboratory test results summarized in the above table, slope stability analysis was conducted for untreated clay, as well as for soil samples treated with 10%, 20%, and 30% charcoal, in order to assess the enhancement in shear strength and overall stability.

B. Slope stability analysis by using Plaxis Software

1) PLAXIS Software

PLAXIS is a finite element software widely used in geotechnical engineering for analyzing soil deformation, stability, and soil–structure interaction. Available in both 2D and 3D versions, it supports applications such as slope stability, foundations, retaining walls, and embankments. The software incorporates advanced soil models like Mohr–Coulomb and Hardening Soil, enabling accurate simulation of real soil behavior under various loading conditions. In PLAXIS 2D, stability analysis evaluates the safety of slopes and foundations using the finite element method (FEM), which provides realistic deformation and failure patterns. The Factor of Safety (FOS) typically ranges from 1.0 to 1.5, indicating the degree of stability.

2) Geometry and Material Propertie

The model used in this study represents a 10 m high zoned embankment constructed over a dense sand foundation with a hard stratum beneath. The embankment consists of an outer shell, a transition layer, and an impermeable core. The upstream slope is 1V:2H, and the downstream slope is 1V:1.75H, with a crest width of 5 m. The core acts as a seepage barrier, the transition layer filters fine particles, and the shell provides structural stability. This configuration ensures an optimal balance between strength, impermeability, and durability, suitable for safe embankment and dam design. The upstream water level is maintained at 7 m, while the downstream water level stands at 1 m relative to the height of the embankment.

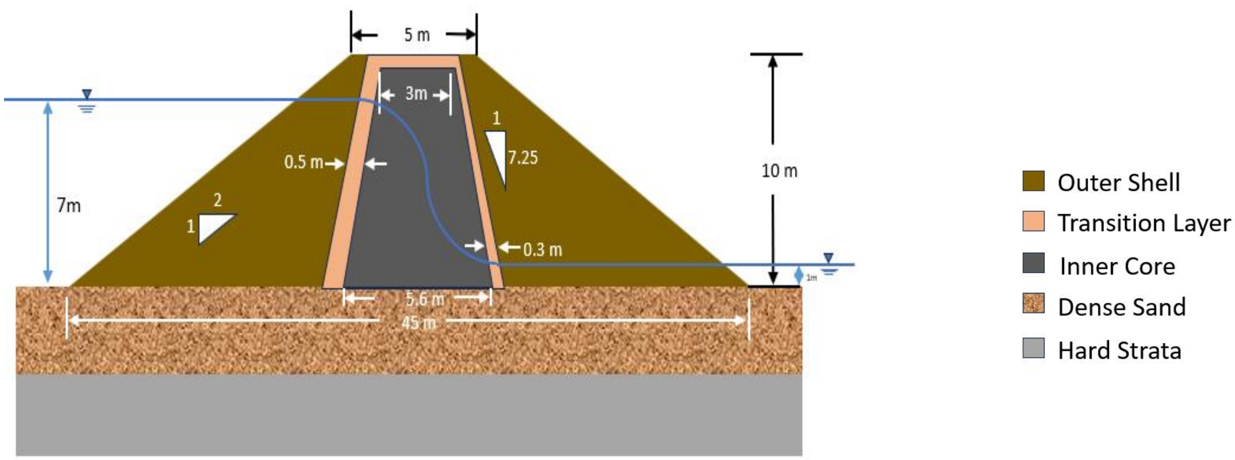

Fig.1 Geometry and materials of embankment

A slope stability analysis was conducted for the clay core using adopted geotechnical parameters γunsat = 15.8 kN/m³, γsat = 18 kN/m³, E = 10,000 kN/m², ν = 0.35, and c = 158 kPa derived from laboratory tests. The analysis produced a Factor of Safety (FoS) of 1.54, which exceeds the minimum requirement of 1.5, indicating that the slope is stable under normal conditions. The results confirm that the clay core possesses adequate shear strength and stiffness to resist failure. Regular monitoring of pore pressure and drainage is recommended to maintain long-term stability and performance.

Table 7: List of material parameters used in the analysis

Material Type	γ_unsat (kN/m³)	γ_sat (kN/m³)	E (kPa)	ν	c (kPa)
Clay (0%)	15.8	18	10,000	0.35	158
10% Charcoal	14.78	16	9,500	0.35	425
20% Charcoal	14.5	17	9,000	0.35	244
30% Charcoal	12.4	15	8,500	0.35	198

Table 8: slope stability analysis results

Mix Type	Factor of Safety (FoS)	Remarks
Pure Clay (0% Charcoal)	1.54	Stable; meets long-term stability criteria
10% Charcoal and 90% Clay	1.53	Improved cohesion; reduced density; stable
20% Charcoal and 80% Clay	1.57	Stable; cohesion decreases compared to 10%
30% Charcoal and 70% Clay	1.56	Stable; excessive charcoal reduces bonding

The comparative assessment of slope stability for the different charcoal–clay mixtures shows that all compositions exhibit acceptable stability, with Factors of Safety (FoS) exceeding the minimum requirement of 1.5 for long-term performance. Pure clay recorded an FoS of 1.54, serving as the baseline and demonstrating adequate shear strength to ensure slope reliability. The 10% charcoal–clay mixture achieved an FoS of 1.53, which is nearly identical to that of the untreated clay; however, this mix benefits from reduced unit weight and significantly improved cohesion, making it a favourable option in terms of both strength enhancement and material efficiency. The 20% charcoal mix produced the highest FoS of 1.57, indicating strong stability due to its lower density and improved pore-pressure dissipation, although its cohesion was lower than that of the 10% mix. Meanwhile, the 30% charcoal mixture yielded an FoS of 1.569, slightly lower than the 20% mix, as excessive charcoal content reduces stiffness and interparticle bonding. Overall, the results reveal that while the 20% charcoal mix offers the highest numerical stability, the 10% mix provides the most balanced improvement in mechanical behaviour, whereas higher charcoal contents begin to compromise cohesion and structural integrity.

Generally, a berm is provided for every 5 m of embankment height; therefore, placing the upstream water level at 7 m ensures a safe margin and contributes to improved overall stability of the structure.

V. CONCLUSIONS

1) The black cotton soil used in this study was classified as CH (highly compressible clay) with poor engineering properties high liquid limit (52%) and plasticity index (21%) indicating significant shrink–swell potential.
2) The natural soil exhibited an Unit weight of 15.8 kN/m^3, optimum moisture content (OMC) of 20%, CBR of 3.00, and UCS of 3.17 kg/cm², confirming its unsuitability for heavy load-bearing applications without stabilization.
3) Addition of charcoal powder modified the soil's behaviour significantly, reduction in plasticity index beyond 20%, indicating improved workability and reduced swell potential.
4) The MDD decreased progressively from 15.9 kN/m^3(5%) to 12 kN/m^3 (40%) due to the lightweight, porous nature of charcoal, showing that excessive charcoal reduces soil compactness.
5) The CBR values improved notably, reaching a peak of 10 at 20% charcoal content, marking it as the optimum proportion for subgrade strength improvement.
6) The UCS values showed maximum strength (8.5 kg/cm²) at 10% charcoal addition, representing a 2.5times improvement over untreated soil; beyond this, strength declined due to reduced density and bonding.
7) Slope stability analysis yielded FoS values of 1.54 for natural clay, 1.53 for the 10% charcoal mix, 1.57 for the 20% mix, and 1.569 for the 30% mix. These results show that moderate charcoal incorporation (10–20%) provides stability levels comparable to that of natural clay, making such mixtures suitable as alternative core materials when good-quality soil is unavailable. However, higher charcoal content (30% and above) reduces both stiffness and cohesion, which in turn decreases the overall stability of the embankment.

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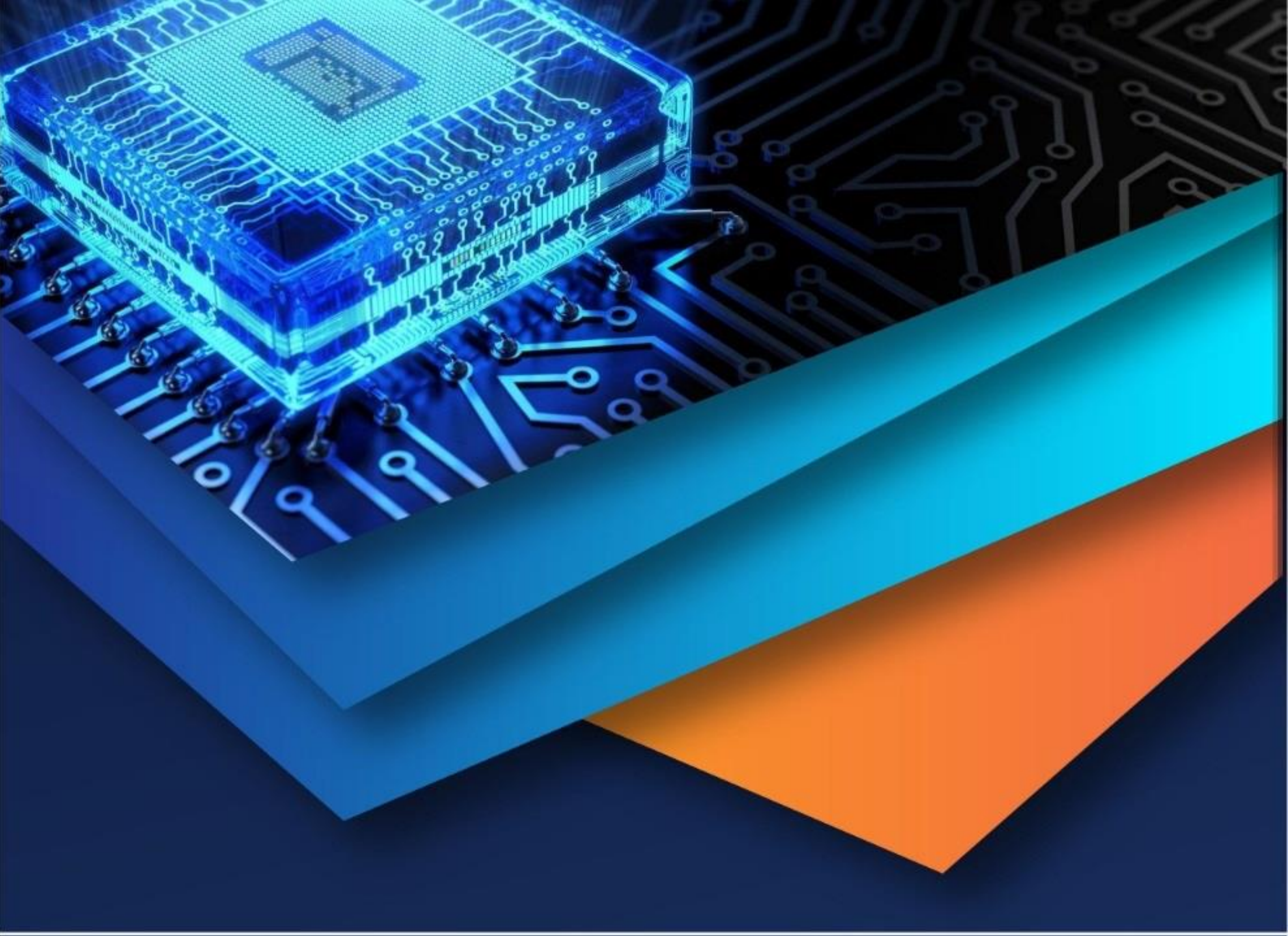

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